Understanding urban resilience with the Urban Systems Abstraction Hierarchy (USAH)

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Abstract:

The paper discusses how the Urban System Abstraction Hierarchy (USAH) can be used as an informative hazard-agnostic tool to understand interdependencies between shocks which impact tangible parts of the city system, and longer-term stressors which impact intangible outcomes of the city system. To create resilient cities, we must grapple with such complex interdependencies. Effective solutions that foster resilience require acknowledging the interplay between sectors (e.g. healthcare systems and ecosystem services), between scales (e.g. local and regional), between timeframes (e.g. immediate shocks and longer-term stresses), and between what we can and cannot see in the physical world (e.g. tangible resources and abstract purposes). These critical 'systems thinking' areas can be explored by mapping urban interdependencies through their functionality, rather than their geospatial connectivity. The aim of this paper is to build and validate the USAH as a resilience tool to do just this. The analysis demonstrates how the USAH tool can make interactions explicit whilst keeping urban complexity tractable. By quantifying interdependencies, fresh perspectives on urban functionality are provided. It concludes that the USAH tool fills an important gap in the resilience literature by helping to operationalise the complexity within urban systems.

Key words: complex adaptive systems, resilience, interdependencies, cascading impacts, abstraction hierarchy, urban systems

1. Introduction

1.1 In reality: Urban resilience and complex system interdependencies

Resilience planning is important because over half the world's population now live in cities, a figure that is set to increase in the future (UN, 2019). Cities are centres for innovation, creativity, technology, prosperity, social development and employment (UN, 2019), all of which make them attractive places to live. This also makes them exposed to a growing number of adversities: from population growth to rising inequalities, from climate change to more frequent and intense environmental hazards, from terrorism to outbreaks of global pandemics. In response, there is a shift from urban policies which are centred around risk assessments to specific hazards, to policies which enhance the performance of the city system when confronted with multiple hazards (Arup, 2015). Resilience planning therefore helps cities to 'endure, adapt and transform' to both expected and unexpected hazards (Arup, 2021). Arup (2015, p.3) define resilience planning as *"*the capacity of cities to function, so that the people living and working in cities – particularly the poor and vulnerable – survive and thrive no matter what stresses or shocks they encounter".

In *Michael Berkowitz*: *A tale of two blackouts* the responses to the New York City blackout in 1977 and 2003 are contrasted (McKinsey & Company, 2016). It states that in 1977, New York City was undergoing an urban crisis, with economic decline, middle-class flight, and disconnected infrastructure. During the '77 blackout, there were reports of widespread crime and looting throughout the city. Conversely, in 2003 there were reports of neighbours looking out for each other during the blackout as the city had outcomes of a resilient city – a stronger economic outlook, integrated police department, improved infrastructure and social cohesion (McKinsey & Company, 2016). These two contrasting events exemplify the interdependencies between shocks (such as a blackout, flood, terrorist attack) and stresses (such as poverty, inequality). Grappling with such real-world interdependencies is essential to planning resilient cities, and while this is widely acknowledged, few tools exist for this purpose. The aim of this paper is to build such a resilience tool.

1.2 In theory: Resilience frameworks and complex systems thinking

The New York City blackout highlights that resilience is not about resisting change and conserving existing structures, but about embracing adaptability, through recognising the interplay between fast changes and longer-term sources of resilience (Folke, 2006). Acknowledging this cross-scale interaction requires system thinking. In systems thinking, the notion of a hierarchy is an important concept to explore interactions across different spatial and temporal scales (Nel, du Plessis and Landman, 2018). Ostrom (2009) argue that identifying and analysing relationships between and across these scales is a core challenge for sustainability in complex systems. In a hierarchy, each element should also be understood as a nested whole that requires identifying which scale analysis is needed within that hierarchy, whilst keeping in mind the wider context (Nel, du Plessis and Landman, 2018). By conceptualising cities as a hierarchy of spatial and temporal scales, we can understand how tangible parts of the city system can interact with intangible resilient outcomes. This requires understanding system components and how they are interrelated (Ostrom, 2009), and how that interrelation gives rise to non-linear cascading impacts (Gunderson and Holling, 2002; Batty, 2012; Rinaldi, Peerenboom and Kelly, 2001; Patorniti, Stevens and Salmon, 2018). Literature on cities as complex systems is plentiful (Amoako, Cobbinah and Mensah Darkwah, 2019). Such complexity can make resilience difficult to operationalise (Desouza and Flanery, 2013; McClymont *et al.*, 2020), resulting in a greater emphasis on theory as opposed to application (Bedinger *et al.*, 2020).

1.3 In practice: Operationalising urban resilience through complex systems mapping

A way to map the wider system and capture these cascading impacts– with detailed analysis of a specific shock or stress, and how they are interrelated – is still lacking (Bedinger *et al.*, 2020). Ribeiro and Pena Jardim Gonçalves' (2019) conceptual review of resilience revealed a lack of operational tools available to evaluate the potential resilience of an urban system beyond conceptual structures. Bedinger *et al.* (2019) review of the hydrohazards literature found a lack of systems methods that can address six complexity concepts (uncertainty, multiple spatial scales, multiple time scales, multimethod approaches, human-nature dimensions, and interactions). A significant gap remains in "resilience operationalisation when going from theory to practice, making resilience tangible and practical for cities" (Marana *et al.*, 2019, p. 3). Moreover, without a systems approach to resilience, siloed views of complex adaptive systems may result in unintended consequences (Bai *et al.*, 2016).

To operationalise resilience planning, an interdisciplinary tool is needed that can be used in tandem with these conceptual frameworks. Tools to do so are beginning to emerge. Wardekker *et al.* (2020) translate the urban resilience concept into operational criteria using the Resilience Diagnostic Tool which distils resilience principles and narratives into a pathway that resilience operationalisation could take. Marana *et al.,* (2019) provide a resilience toolkit for cities to break down organisational silos and encourage the identification of risk dependencies and cascading effects. Herrera (2017) operationalise resilience using systems dynamics modelling to quantify system response to disturbances by focusing on the system structure to identify the mechanisms that contribute to resilience. It identifies ways to influence this response by explicitly quantifying feedbacks and interactions for a casual analysis. What is missing, however, is quantification of cross-sector interactions and the influence of these on long-term resilient outcomes. A tool that explicitly captures multi-scale interactions in a way that keeps complexity tractable is still lacking. One promising method to pursue these aims is the abstraction hierarchy (AH).

The AH is the first step in a socio-technical systems method developed by Rasmussen (1985) to understand system conditions and improve design in the nuclear power sector, and has since been used widely by human factors researchers across multiple domains. Based on human reasoning and adaptation to complexity, the underlying theory and methodology of the AH is entirely compatible with resilience planning. An AH constructs a picture of the whole system – including system outcomes as well as physical resources. With input from experienced system users, an AH supports effective adaptive behaviour to the demands of a wide range of situations (Naikar, 2017). As the AH is an event- and actor-independent method (Jenkins *et al.*, 2011), it can be applied in the context of multiple hazards.

Bedinger et al. (2020) discussed how the AH could be extended from its traditional use in the design of a workplace, factory or plant, to an entire city, creating the Urban Systems Abstraction Hierarchy (USAH). This argues for the AH as a candidate to overcome four obstacles that typically 'block the path' to effective resilience tools: (1) language (by integrating partial views of the urban system across disciplines using common language), (2) scale vs resolution (by providing a wider scaffolding which still supports the 'slotting in' of more detailed technical or process models), (3) breadth vs comprehensibility (by taking a pluralistic approach to modelling that covers many natural, social, and technical subsystems as well as value-laden components), and (4) change (by building a base model that is time- and event-independent, such that it can be easily adjusted for new contexts or future scenarios).

Typically, the AH method is not applied to such a physically large-scale system as an urban area (usually focusing on a single worksite). It thus does not require input from such a large and diverse cast of subject matter experts (usually being generated from desk-based literature review and a few workshop hours with worksite employees). Furthermore it does not typically include any quantitative analysis (usually involving a qualitative discussion aimed at building a shared understanding of the overall system and generating improvements to system design). As such, to apply the AH framework to the urban system, the contribution of this paper goes beyond reporting of a qualitative system model in a new domain, using the traditional methodology. It also requires advancing the AH methodology for robust and transparent application of the method to larger-scale systems, and developing interpretive rules for quantitative analysis that provide insights into key resilience concepts e.g. interdependency.

This paper presents the methodology for constructing the USAH tool and how to apply it in the context of resilience planning. Section 2 details the methodology for constructing the USAH tool, elaborating on how the network was built, and outlining the methodological rules for quantitative analysis of the network. Section 3 describes the results of this exercise, detailing the contents of the final USAH network, and highlighting key results from the quantitative analysis. Section 4 discusses the potential of the USAH approach to address the challenges of planning for resilient cities, before concluding in Section 5.

2. Methodology

The development of the USAH consisted of three main stages: (1) creating the pilot USAH, (2) building the USAH, and (3) application of the model using network metrics (Figure 1). The first stage involved constructing a pilot USAH by applying the AH method to the urban systems domain using Beevers, Walker and Strathie (2016) as a foundation. The next part involved scaling up the AH to an urban system in two main stages: node inclusion and link construction. Node inclusion involved consulting with subject-matter experts to ensure a sensible representation of cities using the Delphi method. Open source software code OSMtidy (Visser-Quinn and Bedinger, 2021a) was used to retrieve OpenStreetMap data, triangulating the inclusion of nodes at the Physical Objects level. Link construction involved author consultation to ensure consistency in capturing interdependencies in functionality. The final stage involved applying network metrics to validate the functional interdependencies across all levels. Supporting code can be found at Visser-Quinn and Bedinger (2020).

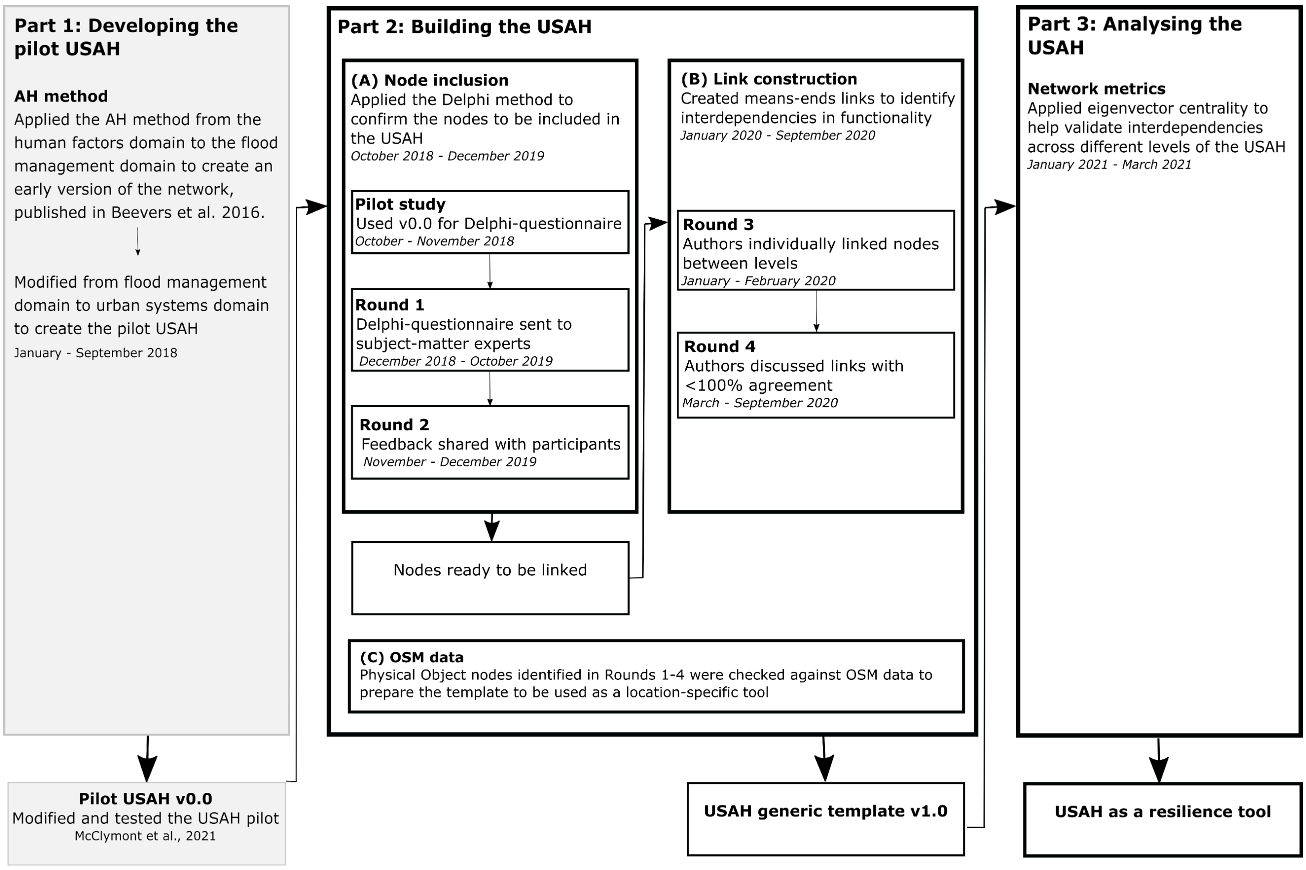


Figure 1 Methodology flowchart for constructing the USAH

2.1 Applying the abstraction hierarchy method to an urban context (Part 1: Developing the pilot USAH)

This section outlines the heuristics of the AH method that were followed to create the pilot USAH.

2.1.1 Defining the system purposes and constraints

In the AH method, a system's purposes and resources place constraints on system behaviour, but still allow "many degrees of freedom for action" within these constraints (Naikar, 2013, p. 16). The purposes that a city can serve for its inhabitants, making them attractive places to live, form the top layer of the USAH. At the bottom of the USAH are all the physical resources within a city boundary. These constraints remain relatively constant in any event, but shape behaviour under a range of circumstances (Naikar, 2013). In other words, the USAH can offer new ways of quantifying and exploring system interactions by capturing functionality of resources and the non-linear means by which we achieve these purposes (Patorniti, Stevens and Salmon, 2018). By focusing on constraints, the USAH acknowledges adaptive processes by seeking to establish how cities could function, as opposed to how they should function (Bedinger *et al.*, 2020).

2.1.2 Decomposing city systems into layers of abstraction

Based on these constraints, the city system is decomposed into discrete parts (nodes) across five different levels of abstraction (Figure 2). Abstraction in this context means the functions of nodes that are separate from the nodes themselves. These levels correspond to different spatial scales within a city boundary. At the bottom of the hierarchy is the lowest spatial scale in terms of discretisation. Resources within a city boundary – such as buildings, ecosystems, facilities, infrastructure - create constraints to form the Physical Objects level (Level 5). Next, the Object-Related Processes (Level 4) explains what each of the objects can physically do (e.g. provide education, provide recreation). The Generalised Functions (Level 3) shows what tasks can be accomplished by using these physical processes. This level represents sectors within a city (e.g. health, economy, transport). The Values and Priority Measures (Level 2) represents outcomes or criteria by which we can determine if the city is fulfilling its Functional Purposes - Level 1 of the hierarchy that identifies constraints based on the fundamental reasons a city exists. Levels 1 and 2 represent the whole city and are more intangible than the physical processes and resources at Levels 4 and 5.

2.1.3 Defining interrelations between layers of abstraction

In order to capture the interrelations between these levels of abstraction, each level is connected through means-ends links – with the nodes at each level becoming increasingly abstract and aggregated moving up the hierarchy. These links capture functionality and are as important as the entities themselves, as they represent “the ‘means’ that a system can use in order to achieve defined ‘ends’”

(Beevers, Walker and Strathie, 2016, p. 203). They are bi-directional: working from the bottom of the hierarchy upwards answers the question of *why* something exists; traveling from the top downwards answers the question of *how* something can be achieved. Figure 3 illustrates the means-ends links using the example Generalised Function node *Employment provision*. Why does *Employment provision* exist in an urban system? To enable *Diverse livelihoods and employment*. How can *Employment provision* be achieved? By *Provide employment,* but also by *Enforce health and safety*. Linking the nodes between levels enables different temporal scales to be analysed. The links between the Functional Purposes and Values and Priority Measures (Levels 1 and 2) are very long-term; between Values and Priority Measures and Generalised Functions (Levels 2 and 3) are long-term; between Generalised Functions and Object-Related Processes are medium-term; and between Object-Related Processes and Physical Objects are short-term. This enables cross-scale and within-scale interactions to be understood in terms of functional interdependencies (Figure 4).

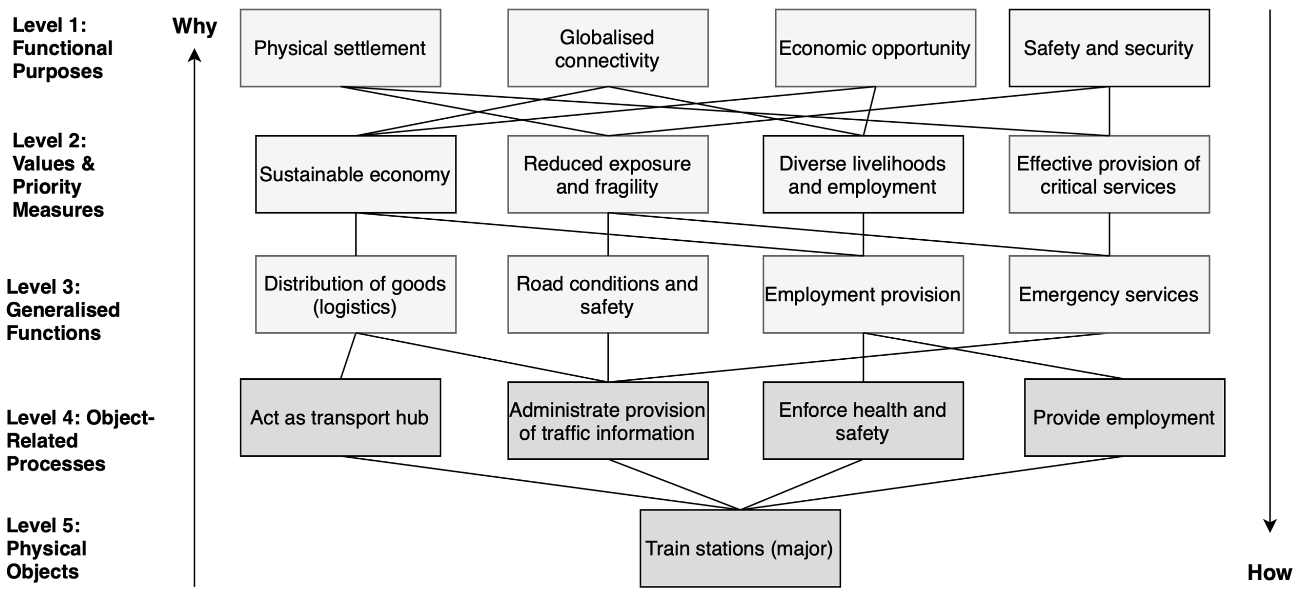


Figure 2 Simplified excerpt of the USAH using Train stations (major) as an example.

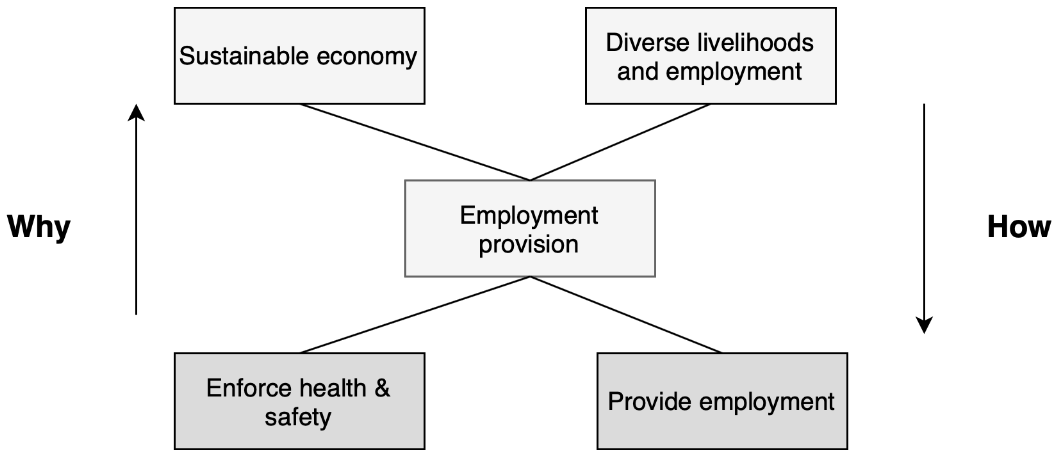


Figure 3 Means-ends links demonstrating how-what-why triad.

2.1.4 Creating the pilot USAH

The pilot USAH built on an early version of the network structure from Beevers, Walker and Strathie (2016). The early Beevers, Walker and Strathie (2016) model was designed specifically for urban vulnerability to flood as a first draft built by academic researchers rather than a wider set of stakeholders to understand urban systems resilience at large. This initial input was adapted at Level 5 to include all Physical Objects found in cities as opposed to those which would only be exposed to a flood (as in the 2016 model). Each Physical Object node refers to the *category* of Physical Objects (e.g. a group of *Cafes* as opposed to individual café buildings). At the Values and Priority Measures level, the Flood Vulnerability Indices (which were embedded in the 2016 model) were replaced with the 12 goals of the 100RC framework, which describe the fundamental outcomes of a resilient city (Arup, 2015). They contribute to a holistic articulation of resilience, where a weakness in one area may affect the overall resilience of a city (Arup, 2015). They are suitable to use as the criteria to measure whether a city is achieving its Functional Purposes because "the goals are based on performance; they describe the outcome of actions to build resilience, but not the actions themselves" (Arup, 2015, p. 8). Moreover, the 100RC framework supports systems thinking and can be applied to any city.

A simplified excerpt of a USAH is illustrated in Figure 2, focusing only on the Physical Object node *Train stations (major).* This example shows that Physical Objects (e.g., *Train stations (major))* enable the Object-Related Processes (e.g., *Act as transport hub*). The Object-Related Processes afford a number of tasks or Generalised Functions (e.g., *Distribution of goods (logistics)*), which contribute to Values and Priority Measures (e.g., *Sustainable economy*) and fulfil Functional Purposes (e.g., *Economic opportunity*). The USAH is essentially a systems map, where system components are interconnected based on functionality *between* levels rather than physical connectivity *within* levels (McClymont *et al.*, 2021). This pilot USAH was tested in McClymont *et al.* (2021) as a 'proof of concept' using a flood scenario case study and network metrics to aid understanding of functional interdependencies in the system when a node is exposed to a hazard (Figure 4). This ensured the method could work before the model was further developed. The methodology to do this is outlined in Section 2.2.

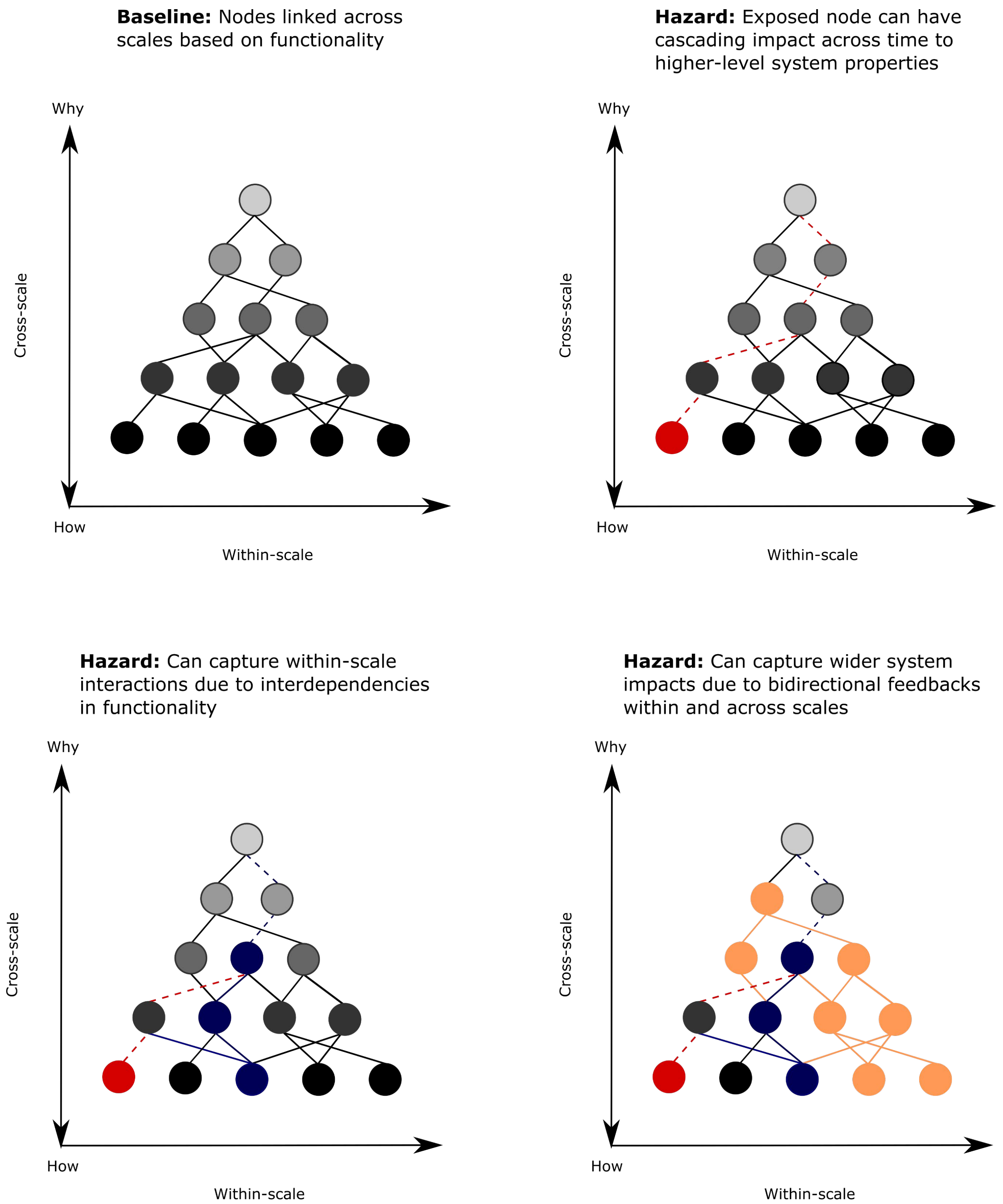


Figure 4 Cross-scale and within-scale interactions in the USAH. Red represents a node that has been exposed to a hazard, blue represents alternative ways the system can achieve its functional purpose if a node is no longer functional, and orange represents cascading impacts as a result of the new system structure.

2.2 Building the USAH: Node inclusion (Part 2A)

A node represents a system component at a particular level of abstraction. Consulting with subject-matter experts on the node inclusion allows the USAH template to be generated in a consistent and transparent manner.

Constructing the USAH can benefit significantly from individual judgements on a collective basis, and is therefore well-suited to the Delphi technique (Grisham, 2009) which has been used in other studies to apply the abstraction hierarchy model (Patorniti, Stevens and Salmon, 2018). The Delphi technique collates individual, subject-matter expert knowledge into group consensus through an iterative questionnaire (Thangaratinam and Redman, 2005; Hasson, Keeney and McKenna, 2000). A reactive two round Delphi study (Helmy et al 2017), where participants are given a list and asked whether they agree or disagree on inclusion, allowed for efficient participation response. The pilot USAH used in McClymont *et al*. 2021 (which contained 222 nodes across the five levels) was used for the first round to guide participants on the USAH content. As the bottom levels of the USAH are the most granular, Physical Objects and Object-related Processes were grouped into categories based on their sector to help participants with the sheer size and complexity of the exercise. These categories included: Accommodation; Ecosystems; Education & professional services; Finance; Food & drink; Government; Healthcare; Industry; Infrastructure; Culture, leisure, recreation & tourism; Religion & major life events; Social support; and Transport & logistics. The Global Industry Classification Standard (SPGlobal, 2018) was used to help group Physical Object nodes where possible. All questionnaires used in the study are available at Bedinger *et al.* (2021) under ‘validation’.

2.2.1 Participants

Purposive sampling was used. This study involved 19 participants across both rounds of the Delphi study with a diverse range of backgrounds from academia (~70%) and the public sector (~30%). The authors have complied with all relevant ethical regulations. Ethics approval was obtained from the

Ethics Committee and informed consent was obtained from all participants who consulted on the construction of the USAH.

2.2.2 Pilot study

The nodes defined in the pilot USAH created by the authors was used as a basis for the Round 1 questionnaire to provide a baseline from which the participants could propose improvements. Participant feedback gathered from Round 1 was used to adjust the format of the questionnaire for Round 2. Both rounds were piloted to ensure the questionnaires were understandable for participants to complete.

2.2.3 Round 1 and 2

Participants were provided an explanation of each level of the USAH along with probe questions for what should be included within that level (Figure 5). Figure 5 illustrates that the Physical Objects (Level 5) and the Object-Related Processes (Level 4) represent the more tangible parts of city functions, whereas the Generalised Functions (Level 3), Values and Priority Measures (Level 2) and Functional Purposes (Level 1) represent the more intangible functions. The purpose of the Round 1 questionnaire was to gather feedback on the included nodes and determine the appropriate level of aggregation. The Round 2 questionnaire fed back an analysis of Round 1 results. The purpose was to share individuals' feedback with all participants and provide them the opportunity to revise previous answers, which is an important element towards reaching consensus (Powell, 2003). The opportunity to add any nodes enabled a sensible representation of city components, and any additional comments on the structure of the USAH at each level ensured that the tool follows the AH method. As there is no set level of consensus to be achieved for the Delphi study (Hasson, Keeney and McKenna, 2000), any node with <100% agreement after Round 2 was discussed amongst the authors until consensus was achieved.

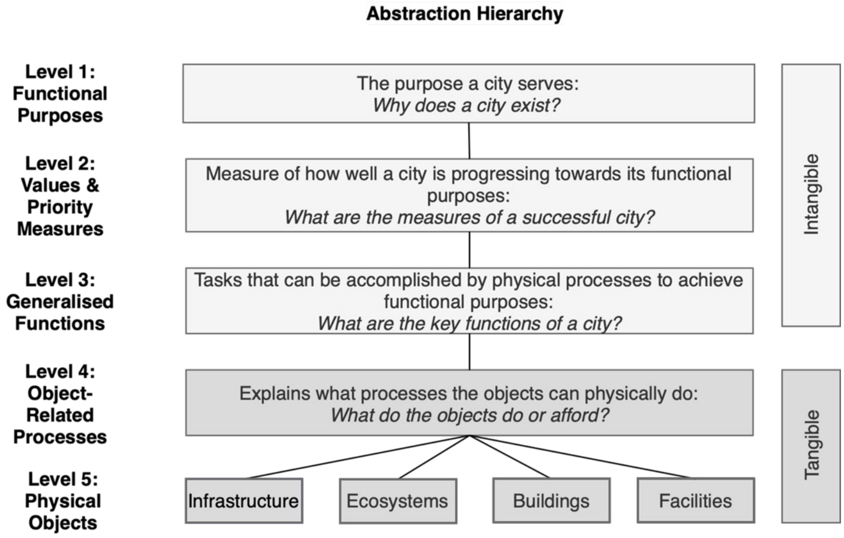


Figure 5 Prompts used in Delphi questionnaire for each level of USAH based on (Jenkins et al., 2008; Patorniti, Stevens and Salmon, 2018 and Naikar, Hopcroft and Moylan, 2005; Naikar, 2017).

2.3 Building the USAH: Link construction (Part 2B)

With nodes agreed for each level, means-ends links were constructed between them to connect the levels based explicitly on node functionality. Whilst inter-rater reliability has been used previously (Beevers, Walker and Strathie, 2016; Patorniti, Stevens and Salmon, 2018) to show agreement in link construction, it was decided that due to the scale of the USAH it would be more beneficial to discuss all links with <100% agreement, to identify inconsistencies and agree on linking rules for where to reflect interdependencies.

2.3.1 Round 3 and 4

In Round 3, the authors were provided with an adjacency matrix of agreed nodes in a spreadsheet format (available at Bedinger *et al.* (2021)) and asked to construct links. This was done two levels (one layer) at a time, creating four spreadsheets each. Performing this exercise independently reduced bias from group thinking and allowed any internal interpretation inconsistencies to be identified. A list of node definitions was provided as well as prompts to help construct links between levels using the how-what-why triad (Jenkins *et al.*, 2008; Naikar, 2013). In Round 4, responses were cross-checked for percentage agreement on which links had been constructed (or not constructed), to identify and discuss those responses with <100% agreement. This took approximately 50 hours of in-person and online sessions (due to COVID-19 restrictions) between the authors, with the lead author facilitating discussions and recording adjustments in a master copy of the USAH adjacency matrix spreadsheet. Once a consensus was reached, the final USAH adjacency matrix was checked for redundant nodes (due to duplicated links).

2.4. Building the USAH: OSM data (Part 2C)

OSM data was retrieved for five UK cities (Edinburgh, Glasgow, Manchester, Bristol and London). This was an additional check for any object types that were not already suggested by the participants, often because they did not come to mind as urban resources (e.g. *Stables*) but nonetheless occasionally exist within a city, and should therefore be included in the baseline model.

OSMtidy, an open source software code written in R (Visser-Quinn and Bedinger 2021a) was used to capture OpenStreetMap (2021) data and identify typical object types across different cities. In brief, OSMtidy uses a shapefile of a city's boundary to extract data from OpenStreetMap (OSM), processes the raw data into a suitable format for filtering into categories, and applies filters to produce a geotagged database of object types (e.g. *Healthcare; Blood bank* or *Sports and games; Recreation ground*). The resulting OSM data can be matched to the USAH Physical Objects. For example, the OSMtidy object type *Sports and games; Recreation ground* is matched to the Physical Object *Sports facilities (outdoor, permeable)*.

Retrieving data from five cities harnessed the power of crowd-mapping, reducing biases from gaps in OSM data from a single specific city e.g. due to how OSM users vary in their approach to tagging and describing geospatial data. Reviewing the OSM data for the five cities involved identifying whether the object types being retrieved could be attributed to any of the existing USAH Physical Objects nodes from previous rounds. This was an iterative process, whereby newly found object types were considered to determine what processes they might afford, then checked against existing Physical Object nodes of a similar type to determine if it afforded similar Object-Related Processes. This occurred in parallel to Rounds 1-4, such that when a newly found object type was thought to have a substantially different, unique set of processes to existing nodes, that object type would be included in the relevant round to fully discuss a new Physical Object node suggestion and determine what Object-Related Processes it should be linked to.

2.5. Analysing the USAH: (Part 3)

In order to analyse the model and enable its use as a tool for quantitative analysis of resilience concepts within the system, appropriate network metrics were identified and applied.

2.5.1: Network metrics

As the USAH depicts a type of network, network metrics can be used to navigate and prioritise interdependencies within the system. The means-ends links between nodes across layers are represented as an adjacency matrix (A). If node i and node j are linked, then A_{ij} it is either equal to one or the associated weight, otherwise it is zero (Segarra and Ribeiro, 2016). Eigenvector centrality (EC) is a metric that determines a node's influence on the network through the importance of its neighbours, and can be given by the following formula:

$$C_E(x) = \frac{1}{\lambda} \sum_{(x,x') \epsilon E} W(x,x') C_E(x'),$$

$$C_E(x_i) = \frac{1}{\lambda} \sum_{(j)} A_{ij} C_E\,(x_i),$$

$$\lambda C_E = A C_{E,}$$

where λ is the maximal eigenvalue scaling factor (Segarra and Ribeiro, 2016). By applying EC to the USAH, a node's relative influence on the overall network can be determined. For example if a node has a high EC then it will have neighbours which are themselves important too (Segarra and Ribeiro, 2016). Eigenvector centrality been shown to measure different layers of functional hierarchy networks (Binnewijzend *et al.,* 2014), and has also been used in complex adaptive systems to understand disaster risk management (e.g. Chen et al., 2020; Clark-Ginsberg, 2020) as well as urban contexts (e.g. Sotomayor-Gómez and Samaniego, 2020), consequently it was considered a suitable metric to understand the structure of the network, and capable of identifying important nodes within it. Due to the imposed hierarchical structure of the USAH, nodes are compared within levels (e.g., Generalised Functions to other Generalised Functions).

All links between nodes have a weight of 1 to establish baseline levels of functionality. This is because the baseline model is assumed as a 'fully functional' goal state in which everything is operating as normal. Further research may introduce adjusted weights that reflect varying effectiveness or functionality of specific links in specific locations; however the aim of this paper is to first build a foundational generic template that can be used for testing this in further studies.

EC can track change in the network, for example, by determining the 'baseline' EC values, introducing a perturbation to the network through altered link weights, and comparing 'new' EC values to the baseline. In order to validate the USAH, the removal of Physical Object nodes 'one-at-a-time' was explored to understand the propagation of changes through to higher levels. This was done by setting the weights of relevant links to 1e-10 as a proxy for zero. This enables the Physical

Object to have null functionality but keeps the overall network structure the same – in terms of number of nodes and links – in order to compare the new network to the baseline.

3. Results

3.1 Node inclusion

This study maintained a response rate of 74% between Delphi Round 1(n=19) and Round 2 (n=15). Each level of the USAH and the corresponding results will be discussed in turn. Table 1 illustrates the variation in the number of nodes included in each round and Figure 6 illustrates the number of nodes added, modified or removed as a result of the feedback from each round. A full list of the node inclusion at each level is available as supplementary materials (a). An interactive version of the USAH, which includes node definitions, can be found at Visser-Quinn et al. (2021b). The generic USAH template can be found at Bedinger *et al.* (2021).

Table 1. 1Number of nodes in USAH included at the start of each round.

Level	**Round 1: Node inclusion**	**Round 2: Node inclusion**	**Round 3 & 4: Means-ends links**	**USAH total**
Functional Purposes	8	9	9	**8**
Values and Priority Measures	12	13	13	**14**
Generalised Functions	29	34	37	**37**
Object-Related Processes	77	217	185	**170**
Physical Objects	96	273	224	**252**
All nodes	222	546	468	**481**

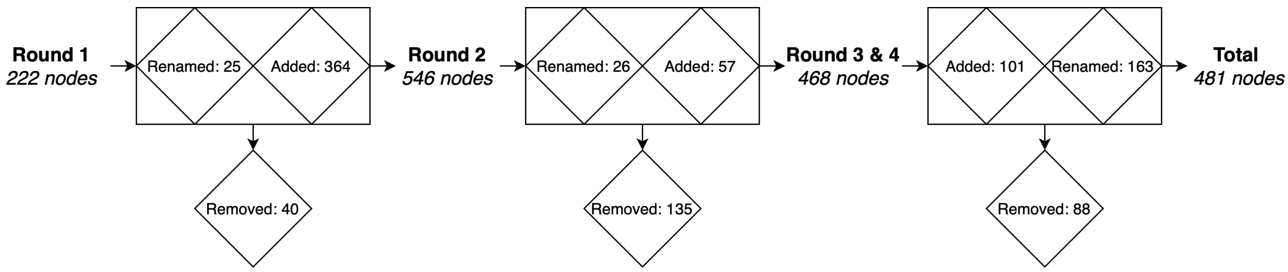


Figure 6 Node inclusion, exclusion and modification for each round.

3.1.1 Physical Objects

The final USAH contains 252 Physical Object nodes, an increase of 156 from the start of Round 1. Feedback from Round 1 was considered alongside a check of OSM data to consistently group object types into Physical Objects with similar functionality and granularity. For example, *Creative spaces* is a single Physical Object node in the USAH, which includes many OSMtidy object types e.g. *Creative spaces; Art studios and centres* and *Creative spaces; Dance studios*.

Rounds 1 and 2 also enabled further verification for applying the AH method to an urban system. The AH was originally designed to be event- and actor- independent (Jenkins *et al.*, 2011), resulting in uncertainty about whether the node *People* should be included as a Physical Object. This node was included in Round 1 as *People* are an interacting part of cities creating constraints within an urban system. It was agreed in subsequent rounds that the USAH should remain actor-independent to illustrate how the system could adapt and reorganise itself based on system processes only, particularly as the aim of the USAH was to explore 'big picture' service provision and system behaviour, rather than the complex behaviour of varied individuals. Moreover, including the node *People* would create a high number of means-ends links from this node, potentially skewing a network analysis.

3.1.2 Object-Related Processes

The Object-Related Processes level specifies the affordances of the Physical Objects within the city system. The final USAH contains 170 Object-Related Processes, an increase of 93 from the start of Round 1.

Feedback from Round 1 and 2 centred around reducing any bias in the number of Object-Related Processes relating to any one participant's sector or interest, and breaking down some Object-Related Processes to reflect distinct aspects and ensure comparable granularity. As an example, *Provide clean water* was disaggregated into the three nodes *Act as access point for potable water*, *Store potable water* and *Transport potable water* which all enable the Generalised Function *Clean water*. Some Object-Related Processes were also moved to higher levels if they were deemed too abstract (e.g. *Environmental conservation* and *Road conditions and safety* became Generalised Functions). This was an iterative process throughout all rounds.

3.1.3 Generalised Functions

The Generalised Functions form the middle level of the USAH. They aggregate the tangible, Object-Related Processes into general tasks a city is expected to perform, which are necessary to achieve city outcomes and, consequently, the Functional Purposes (Patorniti, Stevens and Salmon, 2018). They are the mediators between the tangible and intangible properties of the city system – in other words the connection between what the city system does and what it should do (Jenkins *et al.*, 2008). The final USAH contains 37 Generalised Functions.

3.1.4 Values and Priority Measures

The Values and Priority Measures level establishes the criteria to determine if a city is achieving its Functional Purposes. The criteria should be measurable (Jenkins *et al.*, 2008), therefore the 100RC goals were used as they include a comprehensive guide to measure progress (Arup, 2015). In Round

1, participants agreed with the inclusion of the 100RC goals at this level, however two additional Values and Priority Measures were added as a result of the feedback: *Environmental sustainability* and *Socio-economic equality and equity*. Whilst these are implicit in the 100RC outcomes, participants agreed that these should be explicit, independent outcomes of cities.

3.1.5 Functional Purposes

The Functional Purposes level describes the overall purposes of a city. They remain relatively constant over time and across a range of situations (Naikar, 2013). The results show that a city should achieve eight diverse purposes, all of which contribute to wellbeing within cities and encapsulate the fundamental nature of cities. Round 1 generated the most debate, highlighting some discrepancies between a function and a purpose (e.g. urban ecosystem services), or a means to an end as opposed to a purpose (e.g. freedom of movement and expression). Round 2 moved towards consensus after presenting feedback to the participants.

3.2 Link construction

Means-ends links explicitly connect the physical resources within a system to the abstract outcomes. The bi-directional nature of means-ends links enables them to capture bi-directional relationships that create interdependencies (Petit *et al.*, 2015; Rinaldi, Peerenboom and Kelly, 2001) between city resources and city outcomes.

Constructing these means-ends links independently sparked substantial debate around setting boundaries for the links. To illustrate, in Round 3 the Generalised Function *Employment provision* had 131 means-ends links, and only two of which had 100% agreement between the authors, indicating a lot of uncertainty (Figure 7). Meanwhile the Object-Related Process *Provide employment* had been linked to both *Employment provision* and *Public health* at the Generalised Functions level. Round 4 analysis highlighted that the link between *Provide employment* and *Public health* was a duplication, as this had already been captured lower in the hierarchy more directly through the linking of *Medical practices* to *Provide general healthcare services* (Figure 7). Developing linking heuristics in this way helped disentangle links higher in the USAH.

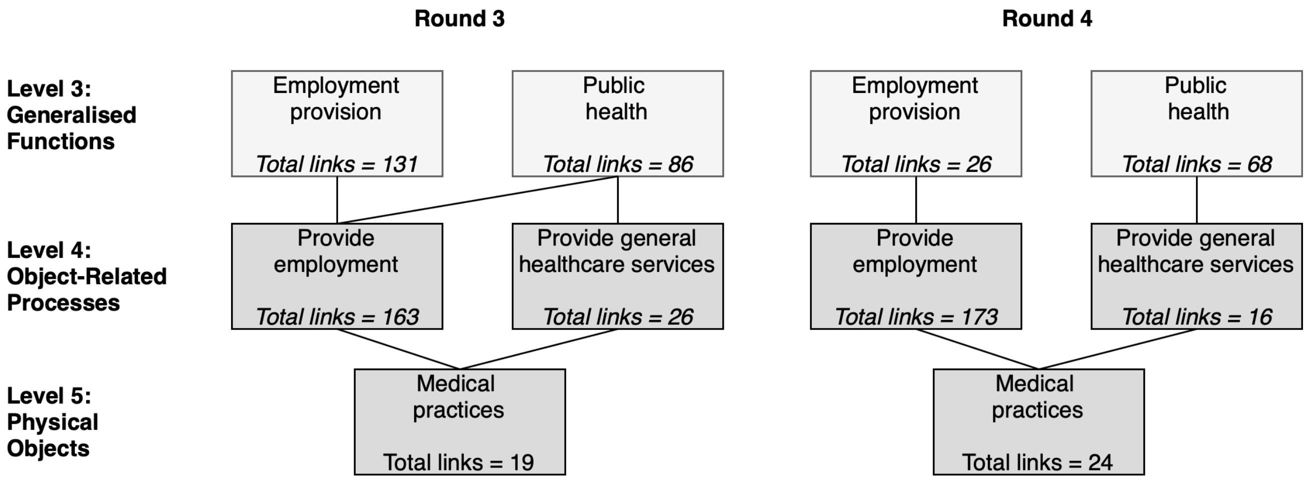


Figure 7 Removal of redundant link between Round 3 and Round 4.

Following Rasmussen's original guidance, "models at low levels of abstraction are related to a specific physical world that can serve several purposes. Models at higher levels of abstraction are closely related to a specific purpose that can be met by several physical arrangements" (Rasmussen, 1985, p. 236). Therefore, in Round 4 there were more links between Physical Objects and Object-Related Processes levels than were made at Generalised Functions, Values and Priority Measures, and Functional Purposes levels. Though the USAH is a 'living' model which can be modified, the end of Round 4 saw fewer and only minor adjustments required, resulting in the final version presented in this work. A possible 49,746 links were considered and discussed, with 9% of these connected in the final generic template USAH. Some groups of nodes could be excluded during this process based on their sector. For example, *Act as mode of transport* could exclude all Physical Objects nodes other than those from the transport sector, allowing the process to be streamlined. The final generic template USAH has 481 nodes and 4463 means-ends links across the five levels of abstraction.

3.3. Functional interdependencies

Eigenvector centrality (EC) was used to validate the USAH and help navigate this large network. EC was applied to the final generic template USAH to identify nodes in each level that have high influence in the overall network. As EC calculates a node's importance based on the importance of its connections more than one level away, it can be used to quantify functional interdependencies within the system. Figure 8 illustrates the distribution of EC values for all nodes across the five levels of the USAH template. Due to the imposed hierarchical structure of the USAH, Physical Object nodes at Level 5 only have up-degree, Functional Purpose nodes at Level 1 only have down-degree, whereas nodes at Level 4, 3 and 2 have both up- and down-degree. This influences the EC value. The imposed hierarchical structure means that some nodes are at a mathematical disadvantage, being at the lowest or the highest level, and thus having less opportunity to be central. Moreover, there are more nodes at the lower levels of the hierarchy. As a result, EC values should only be compared within the same level, and not across. Outliers at Level 4 are *Provide working environment, Act as access point for sanitation, Act as access point for potable water, Act as access point for electricity, Act as access point for telecommunication, Enforce health and safety, Act as access point for food, Act as access point for gas, Provide employment* and *Provide temporary shelter.* These Object-Related Processes have high EC within the network, in other words these processes have many important connections to Level 5 (down-degree) and Level 3 (up-degree), as well as further afield at Level 2 and Level 1. Outliers at Level 3 include *Public health* and *Employment provision.* At Level 2, the outlier is the outcome *Socio-economic equality and equity.* These nodes are less likely to switch rank with other nodes within their level and are therefore influential across a range of hazard scenarios. Table 2 outlines the nodes with a high EC at each level of the USAH. Supplementary materials (b) has the full data set.

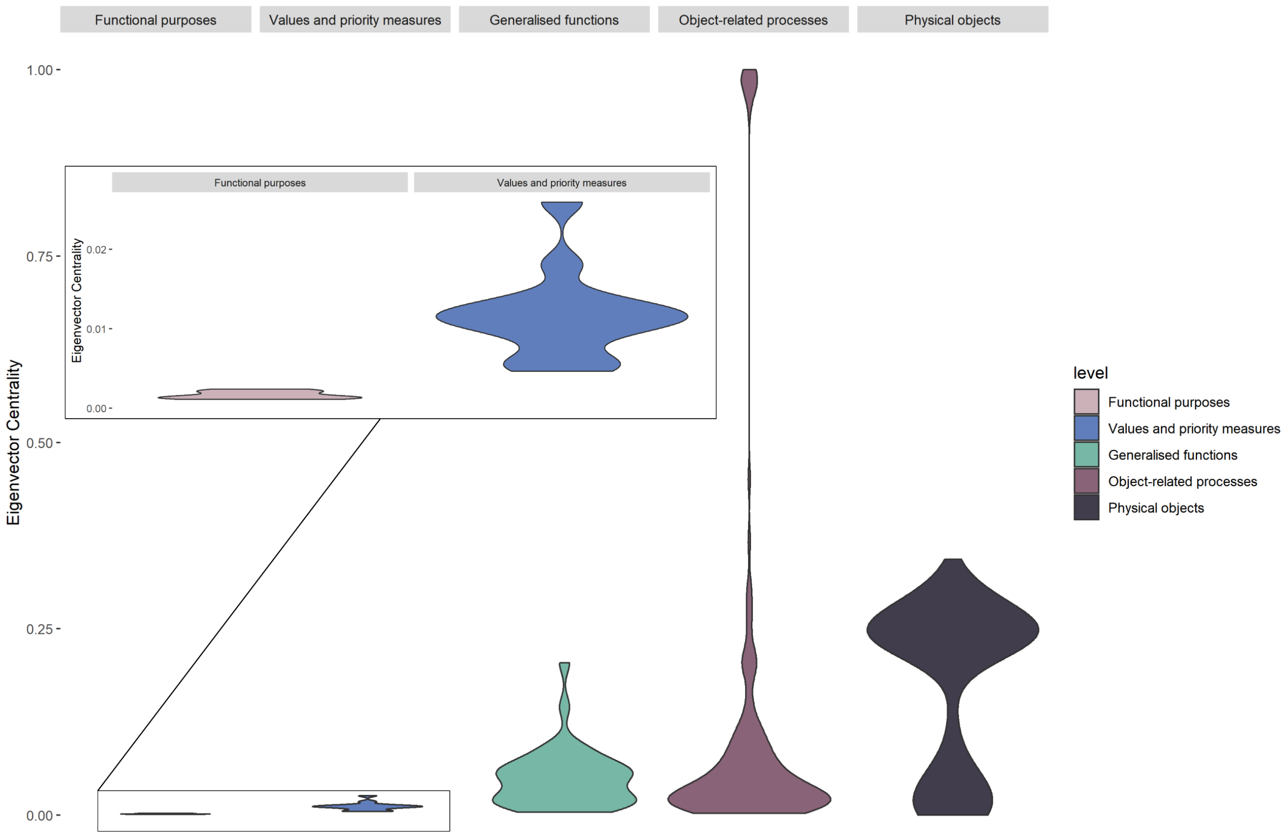


Figure 8 EC distribution of each node in the generic template USAH by level.

Table 2 2Top three nodes with the highest EC at each level of the generic template USAH.

	Node rank within level		
Level	***1***	***2***	***3***
Functional Purposes	Physical settlement	Social opportunity and care	Safety and security
Values and Priority Measures	Socio-economic equality and equity	Minimal vulnerability	Effective provision of critical services

Generalised Functions	Public health	Employment provision	Goods and services provision
Object-Related Processes	Provide working environment	Act as access point for sanitation	Act as access point for potable water
Physical Objects	Higher education	Schools	Botanical gardens

3.4 Incremental removal of Physical Objects

Tests were performed to explore the impacts of removing Physical Objects 'one-at-a-time' on the overall network. In a more structured way, this represents what would happen should an area be hit with a hazard that would impact the functionality of different Physical Objects. This validated the USAH's ability to capture change and cascading impacts through functional interdependence. *Council offices* is presented here as an example as it is linked to a high number of Object-Related Processes (45), has a high EC (ranked 25 within this level), but also allows the role of functional redundancy to be explored. Functional redundancy can be understood as the "existence of several functionally similar components, so that the system does not fail when one of the components fails" (Ribeiro and Pena Jardim Gonçalves, 2019: 7). Table 3 highlights this functional redundancy.

Processes that can be afforded by several different Physical Objects including *Council offices* have high functional redundancy (e.g. *Act as access point for electricity* can be afforded by 173 Physical Objects), whereas some are functionally unique processes that can only be afforded by *Council offices* (*Enforce food standards* and *Enforce building standards*). Removing *Council offices* would also cause other processes to become functionally unique (e.g. *Provide street lighting*). As Figure 9 illustrates, making *Council offices* non-functional reduces the EC of *Enforce food standards* and *Enforce building standards* by 100% as there are no longer any Physical Objects that can afford these processes. The EC of *Provide street lighting* is also reduced by around 60% as there is now only one Physical Object that can afford this process. As shown in Table 3, *Act as access point for* *sanitation, Act as access point for potable water, Act as access point for electricity*, *Act as access point for food*, and *Act as access point for gas*, have very high EC in the baseline and have minimal change after removing *Council offices*. This is because they are all highly connected in the network, meaning that there are a high number of Physical Objects remaining that could afford these processes. These differences in the order of magnitude of change at the Object-Related Processes level validates EC as a metric to explore functional redundancy of the physical resources within a city.

Changes in functional redundancy can be explored at the system level through changes in EC at higher levels. System redundancy can be conceptualised from ecological resilience which "derives from overlapping function within scales and reinforcement of function across scales" (Peterson, Allen and Holling, 1998: 13). Moving up the hierarchy, the most impacted generalised functions after removing *Council offices* were *Governance*, *Waste management* and *Law and order*, all of which are intuitively related to council offices (Figure 9), confirming that the USAH can quantify cascading impacts. Changes in node ranking at this level can also identify what nodes are now having a large influence on the system compared to baseline conditions. *Emergency services*, *Energy supply*, *Learning and education*, and *Social interaction* all increase in node ranking, indicating that they have more relative influence in the network when *Council offices* are removed, compared to baseline conditions where every node is fully functional. *Environmental conservation*, *Governance* and *Foster social cohesion* have less relative influence as a result of removing *Council offices* from the system.

At the more abstract levels, Figure 9 illustrates that all Values and Priority Measures (e.g. *Reliable communications and mobility*) and Functional Purposes (e.g. *Globalised connectivity*) have been impacted as a result of removing *Council offices*. This case study demonstrates that EC can track the impact of a tangible change at a lower level across all higher levels of abstraction. It highlights node changes that one might expect if *Council offices* were rendered non-functional in a city system. However, it also highlights wider system trade-offs within the network, providing further insights into cascading impacts in complex adaptive systems. If a node is not functioning anymore, cascading consequences on its neighbours' nodes are captured through a change in interdependencies across different levels in the USAH, which can be quantified by a change in EC value by comparing a hazard scenario to baseline conditions.

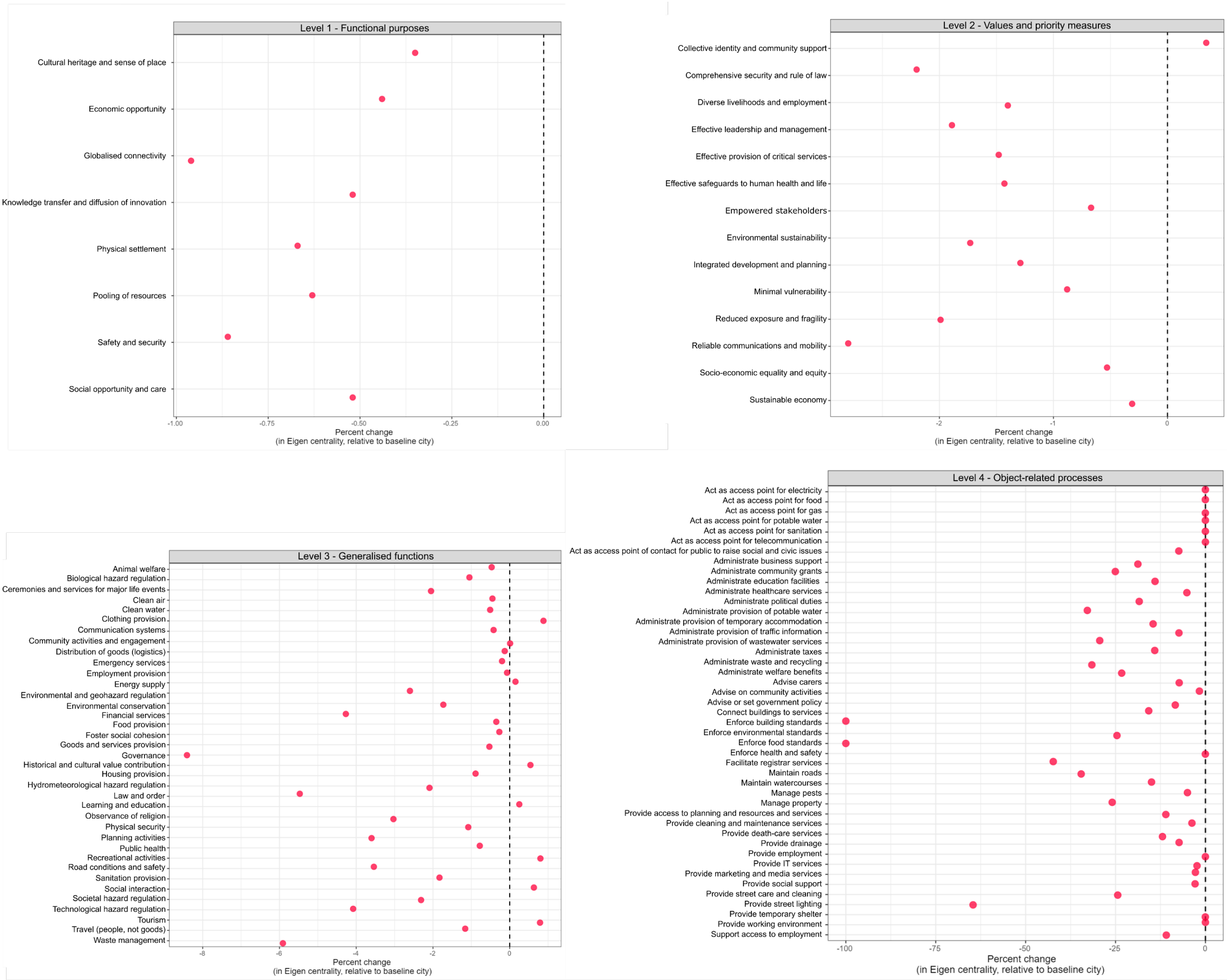


Figure 9 Impact of removing the Physical Object Council offices *across Functional Purposes, Values and Priority Measures, Generalised Functions and Object-Related Processes levels. Note that the Object-Related Processes level only displays processes directly linked to* Council offices *for eligibility.*

Table 3 Object-Related Processes that are impacted by the removal of Council Offices to demonstrate the role of functional redundancy

	Baseline			**Council offices removed**		
Object-Related Process	**Number of linked Physical Objects**	**EC**	**Rank within level**	**Number of linked Physical Objects**	**EC**	**Rank within level**
Act as access point for electricity	173	0.992	4	172	0.992	4

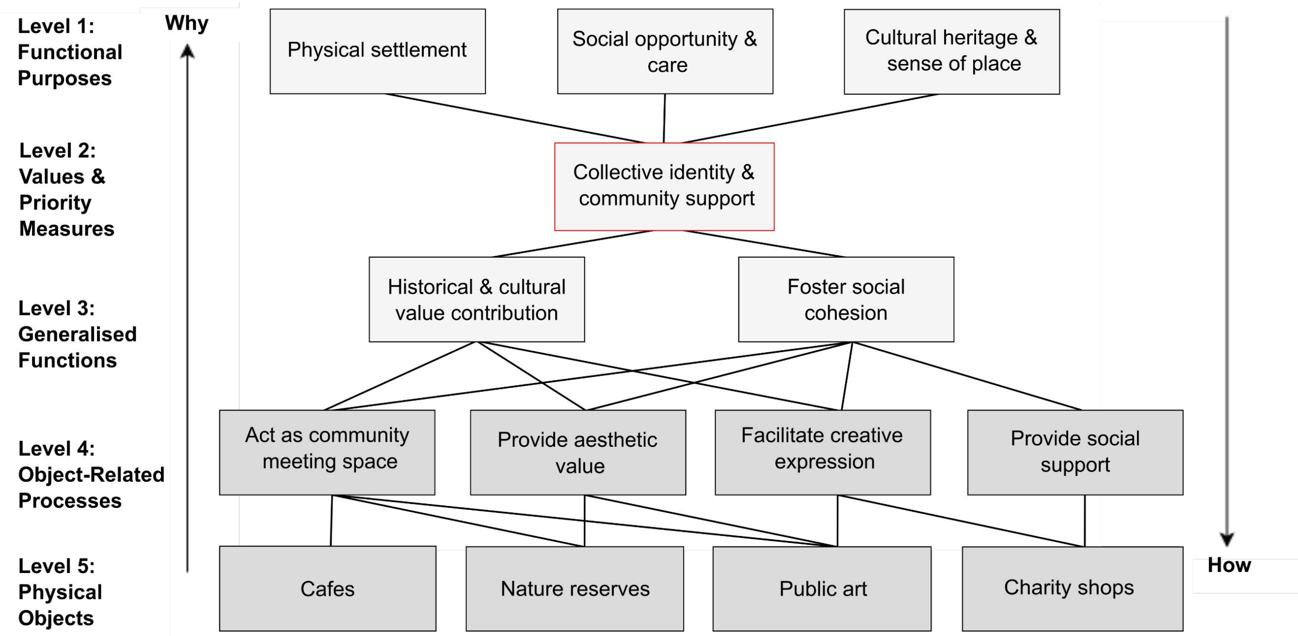
Act as access point for food	168	0.977	7	167	0.977	7
Act as access point for gas	168	0.976	8	167	0.975	8
Act as access point for potable water	172	0.992	3	171	0.992	3
Act as access point for sanitation	172	0.998	2	171	0.998	2
Enforce building standards	1	0.018	124	0	0	N/A
Enforce food standards	1	0.016	135	0	0	N/A
Provide street lighting	2	0.010	152	1	0.004	163

4. Discussion

4.1 Conceptualising resilience by focusing on functionality

This paper proposes the USAH as a different approach to resilience that is distinct from – and adds to – a traditional geospatial hazard-mapping perspective. By taking a functional interdependencies perspective, the USAH allows systems thinking around urban resilience to be 'done' in a new way. The USAH outlines how the physical resources and the fundamental purposes of cities both place functional constraints on system behaviour. Results show how these purposes contribute to overall wellbeing within cities. Urban processes convert resources into tasks in order to achieve the purposes of a city system through these means-ends links. How well these tasks are performing are evaluated by the outcomes of a city. Conversely, the USAH provides a tractable way to understand how intangible resilience outcomes are achieved by more tangible city processes and resources, by explicitly linking them across multiple functional scales. Notably, the USAH allows bidirectional feedbacks to be better understood. Resources and processes are exposed to shocks, which will impact longer-term resilience. How well these longer-term outcomes are being achieved will also determine how well the system responds to short-term shocks.

As an example of the bi-directional feedbacks, *Collective identity and community support* has been identified as a resilience outcome in the 100RC framework and has therefore been included as a Value and Priority Measure. According to Arup (2015) progress towards this goal is indicated by local community support; cohesive communities; strong city-wide identity and culture; and actively engaged citizens. The USAH is a tool that can be used to complement these indicators, by explicitly highlighting the interdependencies between this outcome and the physical resources available within a city. Figure 10 illustrates that *Charity shops* fulfil the process *Provide social support*, which enables *Social cohesion*, contributing to *Collective identity and community support*. When asking how this outcome can be achieved, the USAH highlights interdependencies within the city system that might not be apparent at first glance. An alternative way this can be achieved is through the Generalised Function *Historical and cultural value contribution*, which can be achieved by *Providing aesthetic value*, which can be afforded by *Public art* or *Nature reserves*. By making these interdependencies explicit, the tool provides a more holistic viewpoint, moving away from a purely economic valuation of resources. Insights can then be provided into how wider system interactions contribute to different functions, perhaps in ways previously unexplored (Patorniti, Stevens and Salmon, 2018). A better understanding of these interdependencies offers opportunities for more informed strategies for resilience (Mohebbi *et al.*, 2020).



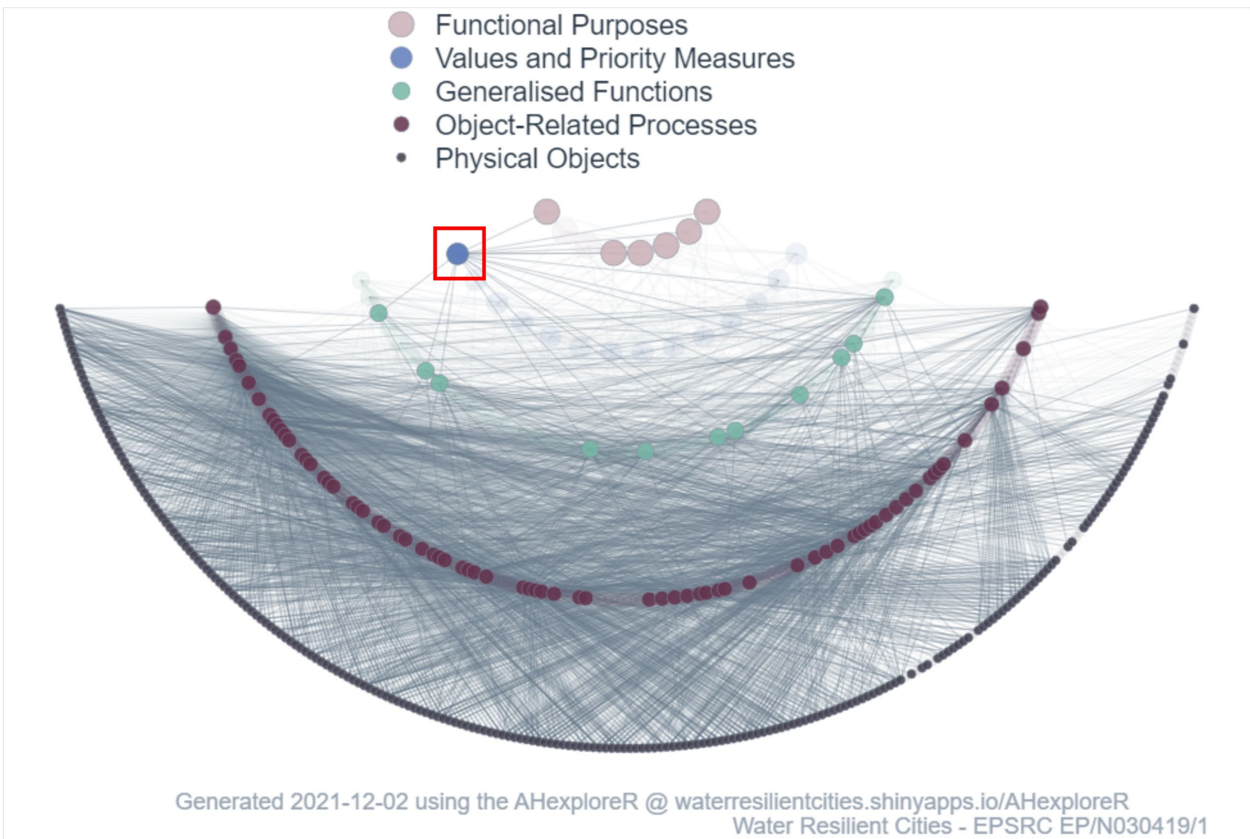


Figure 4 A simplified excerpt of Collective identity and community support *to illustrate the different means to achieve this end, with full subsystem shown.*

4.2 Coping with complexity

This paper has shown how the tool has been built to capture complexity and how it can be applied to resilience planning by exploring cascading impacts and feedbacks across the system. With the USAH, different users can focus on one nested subsystem for analysis without losing the full urban system, as it decomposes the city system into discrete nodes – a key characteristic required in frameworks for complex adaptive systems (Nel, du Plessis and Landman, 2018).

As an example, the outcome *Reliable communication and mobility* has been identified as a Value and Priority Measure. This outcome can be achieved by the task *Communication systems*, which can be achieved by the process *Transmit telecommunications*, which can be afforded by *Telecommunication towers*. A hazard – such as a blackout – would interrupt this process, having a cascading impact on the system's ability to achieve this outcome. But what other processes might be impacted, or become important to the response to that hazard? We know from the New York City blackout example that a stronger economic outlook had a positive influence during the response to the second blackout. In the USAH, *Reliable communications and mobility* is also achieved through the task of *Governance*, which can be achieved by the process *Provide social support* as well as *Support access to employment*, which can be afforded by Physical Objects like *Libraries*, *Charity organisations* and *National government buildings* (to name a few). What if there were more libraries in an area? What if the system's ability to support access to employment was also reduced? What if there were more resources to provide social support? From the previous example, we can see that *Provide social support* is also linked to the outcome *Collective identity and community support*. What might be the knock-on effect of a blackout on this outcome? These are the types of questions that the USAH can explore. By quantifying these explicit connections, it enables a wide range of values and processes to be taken into account and included in decision-making which can enable a more just and sustainable approach to resilience (Bai *et al.*, 2016). Such an approach allows unintended consequences and uncertainty to be explored, improving our understanding of cities as complex adaptive systems.

Urban planners can benefit from 'learning tools' that explore these emergent properties, in order to encourage discussion and critical reflection on planning for resilience (Wardekker *et al.*, 2020). For example, the benefit of green spaces in urban areas can be explored beyond ecosystem services to their direct contribution on resilient outcomes. The USAH can be classified as a learning tool for resilience, as it does not provide clear-cut answers to what is good or bad for resilience. Instead it collates interdisciplinary knowledge, applies this to inform rather than predict the behaviour of cities (Batty, 2012), and explores how cities *could* function under a range of scenarios. Therefore, it can be used to prompt discussion around resilience of 'what' to 'what' (Carpenter *et al.*, 2001).

4.3 Hazard-agnostic resilience

Eigenvector centrality (EC) has been used to navigate the interdependencies and cascading impacts within the USAH. Results show that altering link weights at the Physical Objects level impacts the EC of nodes across all other levels. At the Object-Related Processes level, EC can explore the role of functional redundancy of city resources. Future work could explore the role this has on risks embedded within the system. It could also explore what outcomes are prioritised within urban systems and how (un)equally distributed they are based on the functional interdependencies of available resources. This can be done by filtering the USAH generic template built in this paper for a specific city location. As city data from OSM data was used as a reference point during baseline model development, the USAH does not require further validation when applying it to a specific location. Any resources which are not within a city can be removed from the network; only the Physical Objects level will change, along with any subsequent nodes in higher levels that would be removed as they are no longer supported by any Physical Objects. Thus this is a process of quickly filtering from a comprehensive baseline set, rather than adding or reconstructing through a more time-consuming 'build from the ground up' process. Results from this study show that removing a Physical Object at the bottom level of the USAH creates cascading impacts throughout the intangible levels, which can be measured using EC. The impact of removing resources not within a specific city can therefore be identified by comparing the EC values for the resilient outcomes level for a city location against the generic template.

Using network metrics also enables hazards to be introduced into the system by altering link weights to reflect differences in functionality to explore cascading impacts and system feedbacks. This was tested as a 'proof of concept' in McClymont *et al*. (2021) where a flood shock was introduced to the USAH by altering a nodes functionality between levels 5 and 4 (connecting Physical Objects to Object-Related Processes), in order to identify how the city system adapts as the impact propagates through the wider city network. This was done by comparing each node's network metric value in a test condition to each node's network metric value in a 'normal' baseline condition. The generic USAH template developed in this paper enables this work to be 'scaled up' to the entire urban system and, using OSMtidy, allows the template to be modified for any UK city. As the USAH tool has been built on the assumption that it is both actor- and event- independent, it is now applicable in the context of any hazard at the city scale. By counting and removing Physical Objects within a city boundary, a hazard can be introduced by weighting the Physical Objects based on the proportion of resources remaining functional. The impact of these functional changes across the wider system can be identified by comparing EC values of each node with its baseline value. Longer-term stressors can also be introduced to the USAH by altering the functionality of the Values and Priority Measures level using the 100RC indicators to better reflect the local socio-economic context.

In essence, the USAH is a tractable way to identify how tangible exposure of assets propagates through the wider system to impact outcomes, or conversely how by strengthening an outcome, this propagates through to physical assets in a city. Nel, du Plessis and Landman, (2018) recommend that a framework for complex adaptive systems should allow for a mixture of research methodologies. Real-world data (e.g. smart city data) or outputs from other models (e.g. water balance models) can become inputs to the USAH by altering link weights. Integrating multiple methodologies and subsystems in this way allows for more informed decision-making around managing change. A variety of network metrics could be applied to the USAH to explore exposure, vulnerability, systemic risk and resilience following work by Arosio, Martina and Figueiredo (2020). By explicitly linking the physical with the abstract, the USAH can help explore the interplay between shocks and stresses in a city, previously outlined as being central to resilience.

4.4 Limitations

A limitation of the node inclusion was the balance between granularity and tractability of the USAH. More granular OSM data enabled the USAH to become more complete, and care was taken to ensure this did not result in bias in the Physical Objects toward only what can be 'counted'. Moreover, the increased granularity of the Physical Objects and consequently the Object-Related Processes means the USAH is based on a Western city (specifically the UK). Future work could create and compare a USAH for a city in a different geographical setting using a similar methodology. The construction of the means-ends links was undertaken by the authors. Whilst more participants might have improved the robustness of the percentage agreement, the aim was to generate an informed discussion with participants who were familiar with the method in order to agree best-practice heuristics for constructing an AH at this scale.

A limitation in the application of the USAH is that it does not directly take account of urban inequality, rather this is implicit in terms of physical assets included within the city boundary. In order for resilience to be truly transformative, the USAH should be used alongside other methods which address not only resilience of 'what' to 'what', but importantly resilience for *'whom'* (Cutter, 2016), including resilience frameworks which are power-sensitive (Dewulf *et al.*, 2019). Moreover, the USAH only captures positive functionality, as it has been developed to frame urban systems and service provision around the higher-level constraints of what the system *should* do. Any negative functionality is only captured via the absence or degradation of a link. For example, an Object-Related Process *Produce water pollution* does not exist, only *Support water purification*.

5. Conclusion

This paper set out to build a much-needed tool that maps urban interdependencies, supports systems thinking, and operationalises resilience. The result is an Urban Systems Abstraction Hierarchy (USAH) that allows for consistent comparisons to be made both within and across different cities. Validation exercises show that the USAH is able to track the diverse functionality of physical resources within a city, and how these are interrelated across multiple scales to influence resilient outcomes in the wider city system. A significant contribution of the USAH is its ability to link the physical with the abstract through functional interdependence. The power of the tool affords exciting opportunities for both researchers and practitioners. By identifying system constraints, the USAH can begin to explore emergent properties under a range of circumstances. Future work will explore the use of different network metrics to investigate key interdependencies and how these change under a range of hazard scenarios by altering link weights to analyse different resilient concepts. In doing so, the USAH can bring us one step closer to grappling with complex interdependencies, and fostering urban resilience.

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